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TECHNICAL REPORT RH-83-1

THE HEATING AND FAILURE OF MICROELECTRONIC WIRES
FROM AN ELECTRIC PULSE

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Pulse Effect in Wires   Wires

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

A derivation was made of equations governing the temperature profiles in microelectronic wires. Using these equations, the profiles were plotted for gold and aluminum wires at the minimum voltages required for failure and at two higher voltages. Curves were also plotted for the time required to reach the melting point of the wires as a function of the applied voltage. Finally, curves were plotted for the energy required to raise the wire temperature to the melting point as a function of applied voltage.

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LIST OF SYMBOLS

C_p heat capacity, joules $g^{-1} {}^{\circ}C^{-1}$

I electrical current, amperes

k thermal conductivity, watts $cm^{-1} {}^{\circ}C^{-1}$

k_e electrical conductivity, $ohm^{-1} cm^{-1}$

L length, cm

Q thermal energy, joules

q_x heat flux in the x-direction, watts cm^{-2}

R wire radius, cm

S_e heat from electrical dissipation, watts cm^{-3}

T temperature, $^{\circ}K$

T_o initial temperature, $^{\circ}K$

t time, sec

Δt increment in time, sec

V electrical potential, volts

x longitudinal coordinate, cm

Δx increment in the longitudinal coordinate, cm

α thermal diffusivity, $cm^2 sec^{-1}$

ρ density, $g\ cm^{-3}$

I. INTRODUCTION

In the functioning of microelectronic circuits, it is common for impulsive conditions to exist--either unplanned or by design. It would be convenient for the designer to have an approximate idea as to the tolerance of his circuit for such high electrical stresses that last for very short periods. An investigation of damage modes for circuits subjected to extremely short pulses showed that the most prevalent type of damage was a burnout or melting of the fine gold or aluminum lead wires that are used for making connections. A photomicrograph of such a failure is shown in Figure 1.

The burnout of a fine wire is similar to the burnout of a fuse. In the case of a wire, the information of greatest concern is how long the wire can tolerate a pulse of a given strength before damage sets in. In the case of a fuse, the greatest interest is in the time required to open the circuit, which includes melting time and arcing time. Fuses have been examined by a number of investigators[1-3] in recent years.

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II. THEORY

The theoretical analysis of a wire subjected to a potentially damaging pulse, starts with a heat balance on a transverse slice of the wire having a slice thickness of Δx. A diagram of the model is shown in Figure 2.

Heat Balance on Slice $\pi R^2 \Delta x$

initial rate in at x	final rate in at x	average rate in at x
$\pi R^2 q_x$	$\pi R^2 q_x + \frac{\partial}{\partial t}(\pi R^2 q_x)\Delta t$	$\pi R^2 q_x + \frac{1}{2}\frac{\partial}{\partial t}(\pi R^2 q_x)\Delta t$

where q_x is the heat flux in the x-direction.

$$\underline{\text{avg rate in at x}} \quad - \quad \underline{\text{avg rate out at x} + \Delta x}$$

$$\left[\pi R^2 q_x + \frac{1}{2}\frac{\partial}{\partial t}(\pi R^2 q_x)\Delta t\right] \; - \; \left[\pi R^2 q_x + \frac{1}{2}(\pi R^2 q_x)\Delta t + \frac{\partial}{\partial x}\left\{\pi R^2 q_x + \frac{1}{2}\frac{\partial}{\partial t}(\pi R^2 q_x)\Delta t\right\}\Delta x\right]$$

$$+ \quad \underline{\text{rate of production}} \quad = \quad \underline{\text{rate of accumulation}}$$

$$+ \quad \pi R^2 S_e \Delta x \qquad = \qquad \frac{\partial}{\partial t}\left[\pi R^2 \rho C_p (T - T_0)\Delta x\right]$$

where S_e is the rate per unit volume of heat production by electrical dissipation.

Totalling the above heat balance:

$$-\frac{\partial}{\partial x}\left\{\pi R^2 q_x + \frac{1}{2}\frac{\partial}{\partial t}(\pi R^2 q_x)\Delta t\right\}\Delta x + \pi R^2 S_e \Delta x \; = \; \frac{\partial}{\partial t}\left[\pi R^2 \rho C_p (T - T_0)\Delta x\right] \; . \qquad (1)$$

Dividing by $\pi R^2 \Delta x$ and allowing Δt to approach zero,

$$-\frac{\partial q_x}{\partial x} + S_e \; = \; \rho C_p \frac{\partial T}{\partial t} \qquad\qquad\qquad . \quad (2)$$

By Fourier's Law, $q_x = -k\frac{\partial T}{\partial x}$ $\qquad\qquad\qquad\qquad\qquad\qquad . \quad (3)$

And letting, $\iota = \frac{k}{\rho C_p}$ $\qquad\qquad\qquad\qquad\qquad\qquad\qquad . \quad (4)$

Equation (2) becomes, $\dfrac{\partial^2 T}{\partial x^2} - \dfrac{1}{\iota}\dfrac{\partial T}{\partial t} = -\dfrac{S_e}{k}$ $\qquad\qquad\qquad . \quad (5)$

The following set of boundary/initial conditions applies.

B.C. when $x = 0$, $T = T_0$ for all t

B.C. when $x = L$, $T = T_0$ for all t

I.C. when $t = 0$, $T = T_0$ for all x

The solution to equation (5) is given by Carslaw and Jaeger[4],

$$T - T_0 = \frac{S_e \alpha t}{k} \left\{ 1 - 4 \sum_{m=0}^{\infty} (-1)^m \left[i^2 \mathrm{erfc} \frac{mx+L}{2\sqrt{\alpha t}} + i^2 \mathrm{erfc} \frac{(m+1)L-x}{2\sqrt{\alpha t}} \right] \right\} \qquad . \quad (6)$$

Letting, $\quad S_e = \dfrac{I^2}{k_e}$ $\qquad\qquad\qquad\qquad\qquad\qquad\qquad . \quad (7)$

where k_e is the electrical conductivity of the wire,

And letting, $\quad I = \dfrac{V}{L} k_e$ $\qquad\qquad\qquad\qquad\qquad\qquad . \quad (8)$

Gives, $\quad S_e = \dfrac{V^2}{L^2} k_e$ $\qquad\qquad\qquad\qquad\qquad\qquad . \quad (9)$

In the case of $L = .1$ cm (typical) and $t < 250$ μsec, for gold and aluminum wires, the expression inside the braces approaches 1. In such a case, and with the use of equation (9), equation (6) becomes,

$$T - T_0 = \frac{V^2 \alpha t k_e}{k L^2} \qquad\qquad\qquad\qquad . \quad (10)$$

from which the lifetime t can be calculated for any given voltage and melting temperature. In those cases where $t > 250$ μsec, the entire equation (6) must be used.

There is a minimum voltage below which the melting point of the wire cannot be reached because heat is being conducted out of the wire at the same rate that it is being generated. In this case, there is no accumulation term in equation (1) and the heat balance results in

$$\frac{d^2 T}{dx^2} = -\frac{S_e}{k} \qquad\qquad\qquad\qquad . \quad (11)$$

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With the boundary conditions:

B.C. when $x = 0$, $T = T_0$

B.C. when $x = L$, $T = T_0$

The solution is:

$$T - T_0 = \frac{S_e}{2k}(Lx - x^2) \qquad . \qquad (12)$$

At the midpoint where the temperature is maximum $(x = \frac{L}{2})$, and using equation (9), equation (12) becomes,

$$T - T_0 = \frac{V^2}{8T_0}(\frac{k_e T_0}{k}) \qquad , \qquad (13)$$

where the expression inside the parentheses is the reciprocal of the Lorenz number.[5] The advantage of using the Lorenz number is that it is only a very weak function of temperature, varying no more then two percent between 0°C and the melting point in the case of aluminum and gold. Equations (6) and (10) cannot be made temperature insensitive through the use of the Lorenz number because α is a function of temperature. In this case, a value for α may be used which is that for aluminum or gold at the temperature halfway between 0°C and the melting point.

The amount of energy necessary to raise the wire from ambient temperature to the melting point is,

$$Q = \rho \pi R^2 L C_p (T - T_0) \qquad . \qquad (14)$$

Equation (10) or (6) may be substituted into (14) whichever applies. Using equation (10), equation (14) becomes,

$$Q = \frac{\pi R^2 V^2 t k_e}{L} \qquad . \qquad (15)$$

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III. RESULTS

By means of equations (12) and (13), the temperature profiles of the wires at the minimum voltage were calculated. These wires were assumed to be either aluminum or gold, 0.1-cm long and .001-inch (.0025 cm) in diameter, welded to an infinite heat sink maintained at 0°C, at both ends. Temperature profiles were also calculated for the minimum voltage, but for times less than infinite, to show the temperature of all parts of the wire during the heating process. The curves for the minimum voltage on gold wire are given in Figure 3 and for aluminum wire in Figure 4.

Using equation (16), the temperature profiles of wires at intermediate voltages were calculated. These are shown for gold in Figure 5 and for aluminum in Figure 6. It will be noted that in these two figures there are shown a flattening of the profile, especially at the shorter time intervals. Temperature profiles at high voltages (1 volt for gold wire, .8 volt for aluminum wire) are given in Figures 7 and 8, respectively. It can be observed that the profiles are very flat in these cases, showing that a sizable portion of the central part of the wire reaches the melting point at the same instant. This can also be observed in Figure 1, which shows a large gap melted out of the center.

Based on equation (6), the time required to reach the melting point of the wire (lifetime of the wire) at various voltages is plotted in Figure 9. The amount of energy necessary to melt a wire is shown in Figure 10. In all cases, the pulse is presumed to be a step function.

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IV. CONCLUSIONS

A. For a gold wire .001-inch (.0025 cm) in diameter and 0.1-cm long, subjected to a pulse of zero risetime and zero falltime and a steady voltage between, the minimum voltage needed to produce damage is .234 volt. This presumes both ends to be welded to an infinite heat sink at 0°C. For an aluminum wire under identical conditions, the value is .179 volt.

B. If the square pulse is raised to .3 volt, the aluminum wire will start to melt in .71 millisecond, while the gold wire will reach the melting point in .87 millisecond. In both cases, only the center point of the wire reaches the maximum temperature in the allotted time.

C. At .5 volt and above, both gold and aluminum wires ha   the same lifetimes at the same voltages. At high voltages, the entire   itral section of the wire reaches the melting point simultaneously.

D. At high voltages, a gold wire requires .00069 joules   reach the melting point while aluminum wire requires .00049 joules. Be   ⌐ volt, both types of wires require considerably more energy, as show⋅ ⊢ ⌐igure 10.

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Figure 1.
Gold wire with the central section melted away (magnification: 63X)
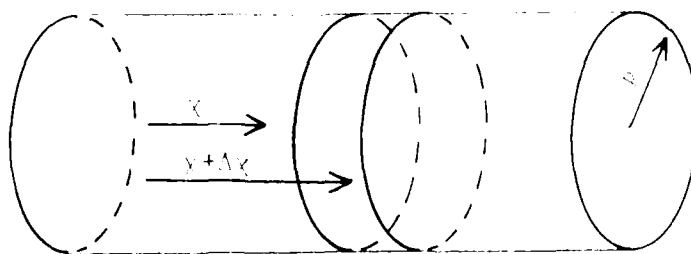
Figure 2.   Model of a wire heated by electrical dissipation
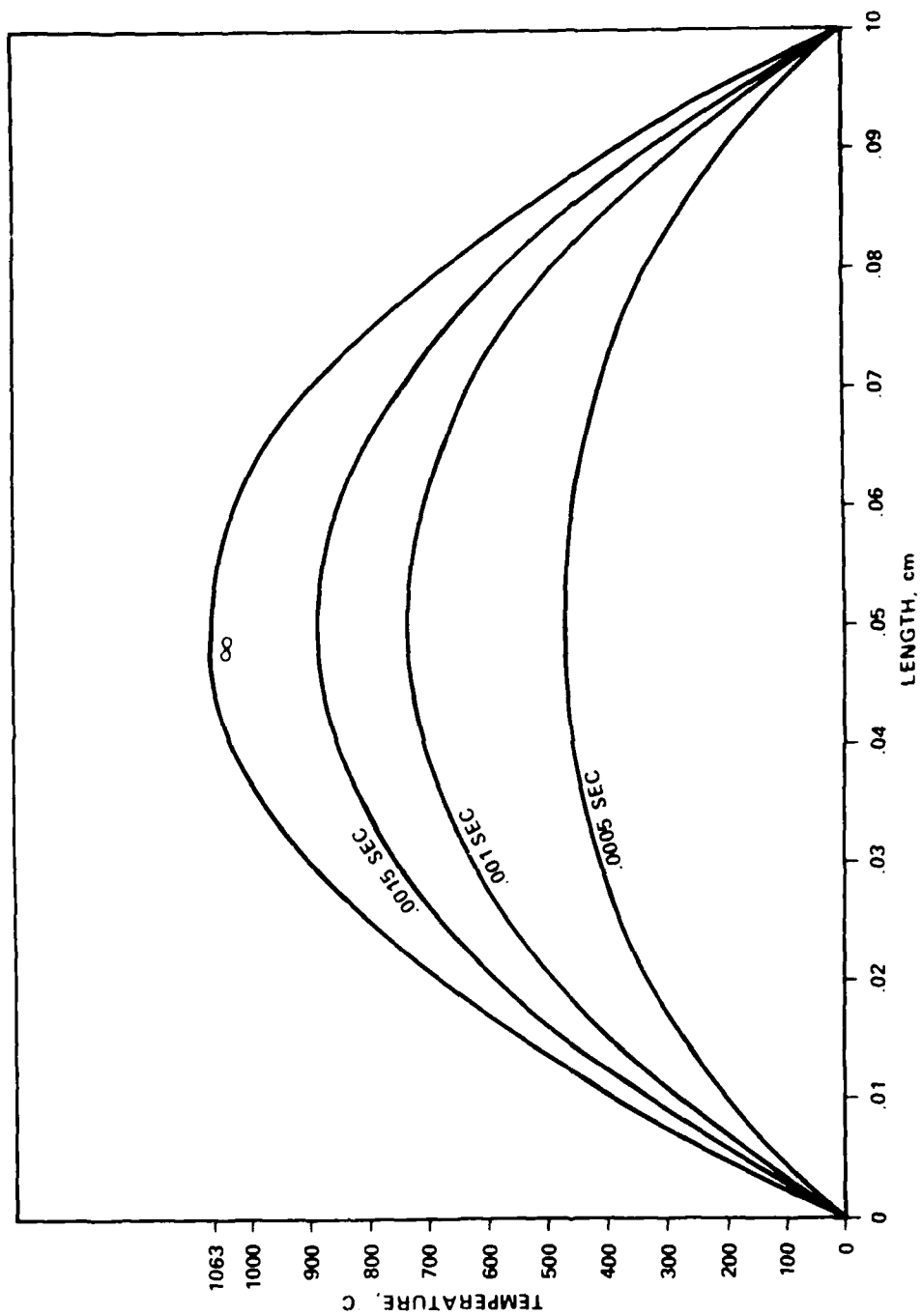
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Figure 3. Temperature profile of a .001-inch diameter gold wire under a .234-volt square pulse load
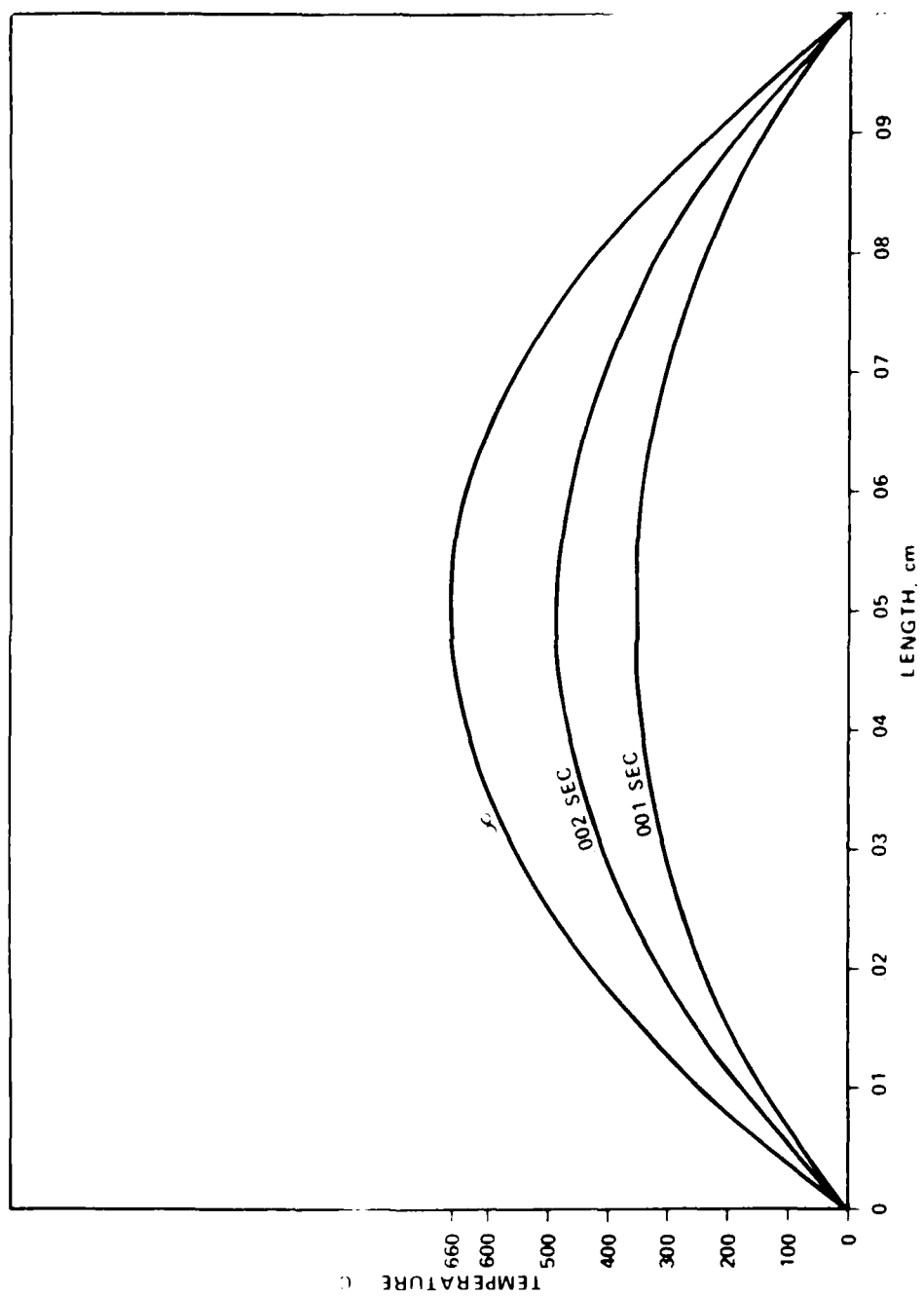
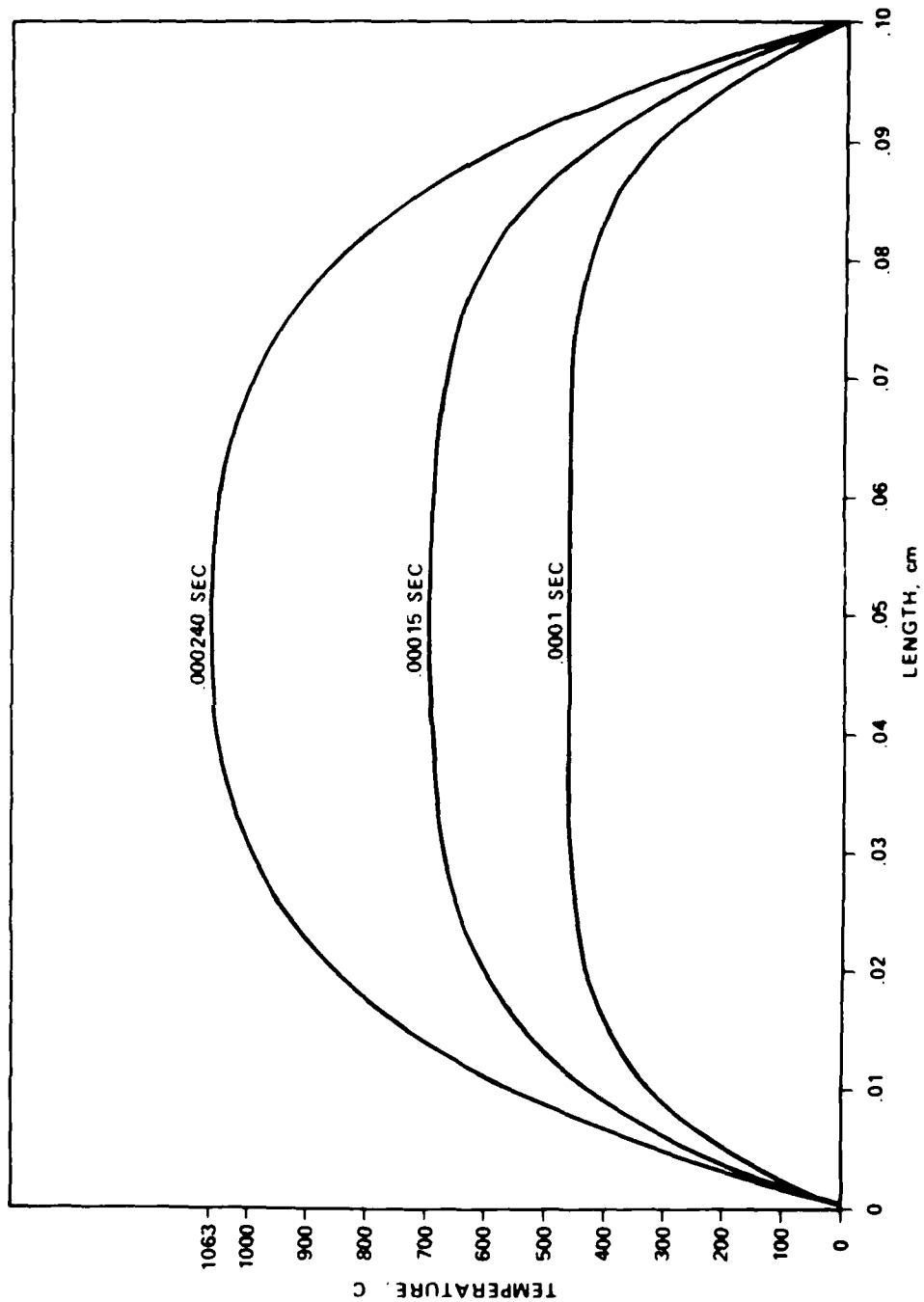Figure 1. Temperature profile of a .001-inch diameter aluminum wire under a .2-volt square pulse load

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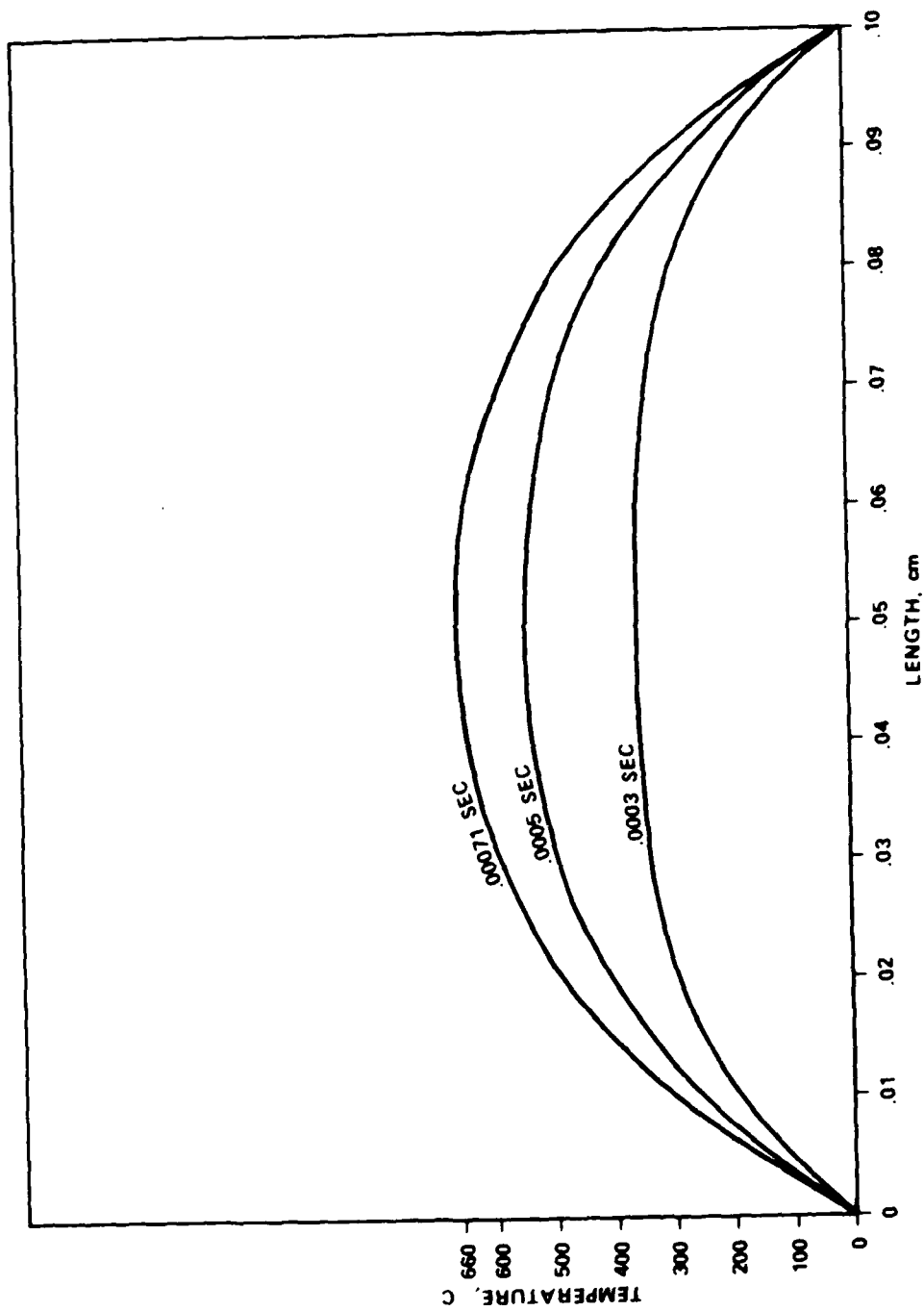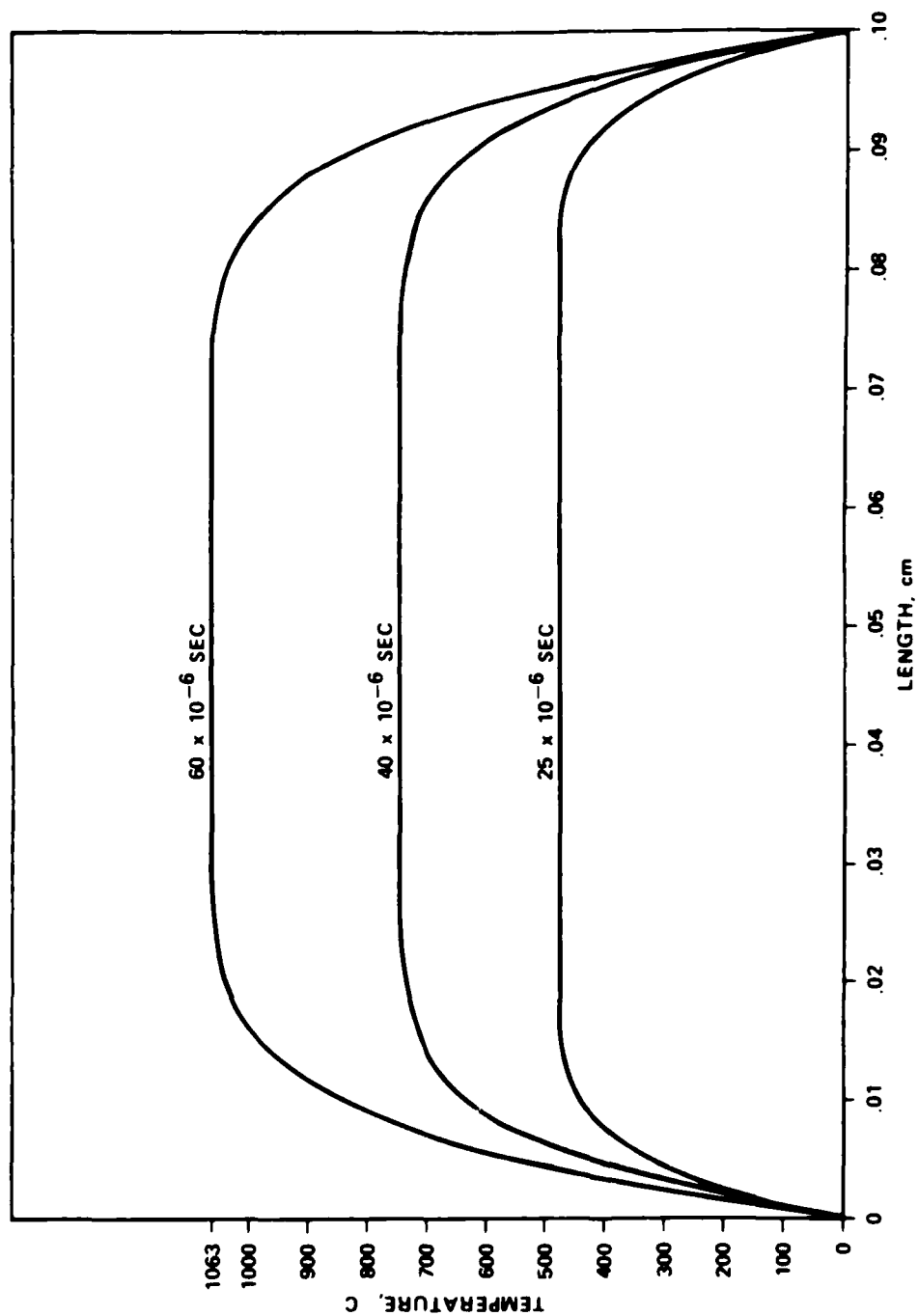Figure 5.   Temperature profile of a .001-inch diameter gold wire under a .5-volt square pulse load
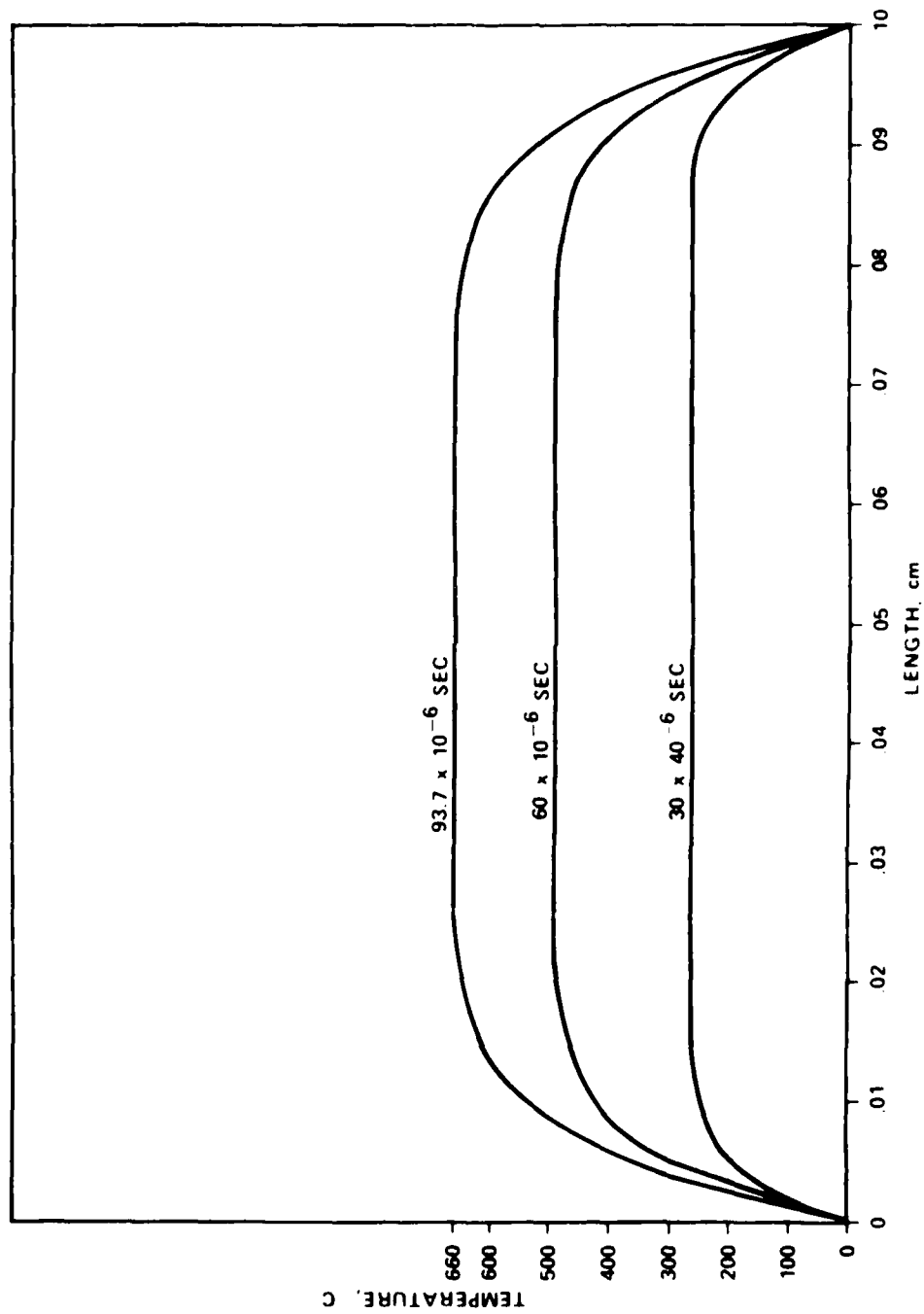
Figure 6.   Temperature profile of a .001-inch diameter aluminum wire under a .3-volt square pulse load

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Figure 7.   Temperature profile of a .001-inch diameter gold wire under a 1-volt square pulse load

Figure 8. Temperature profile of a .001-inch diameter aluminum wire under 1..-volt square pulse load
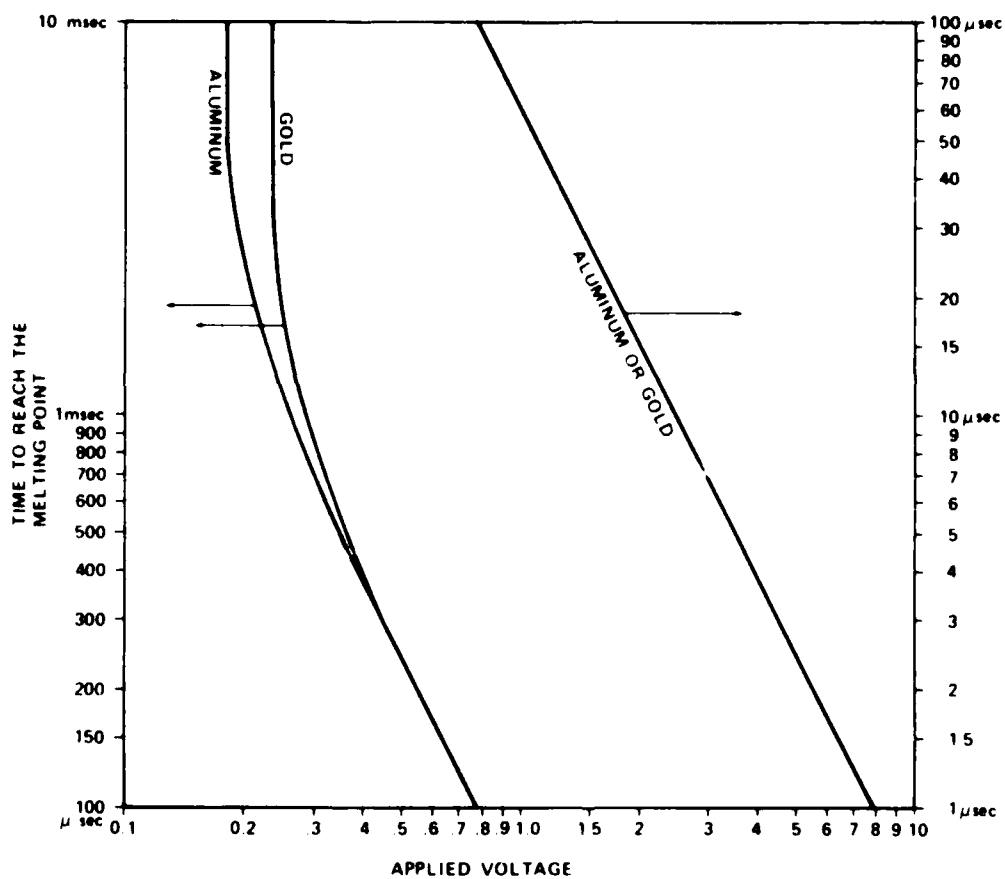
Figure 9.   Time to reach the melting point of .001 inch diameter
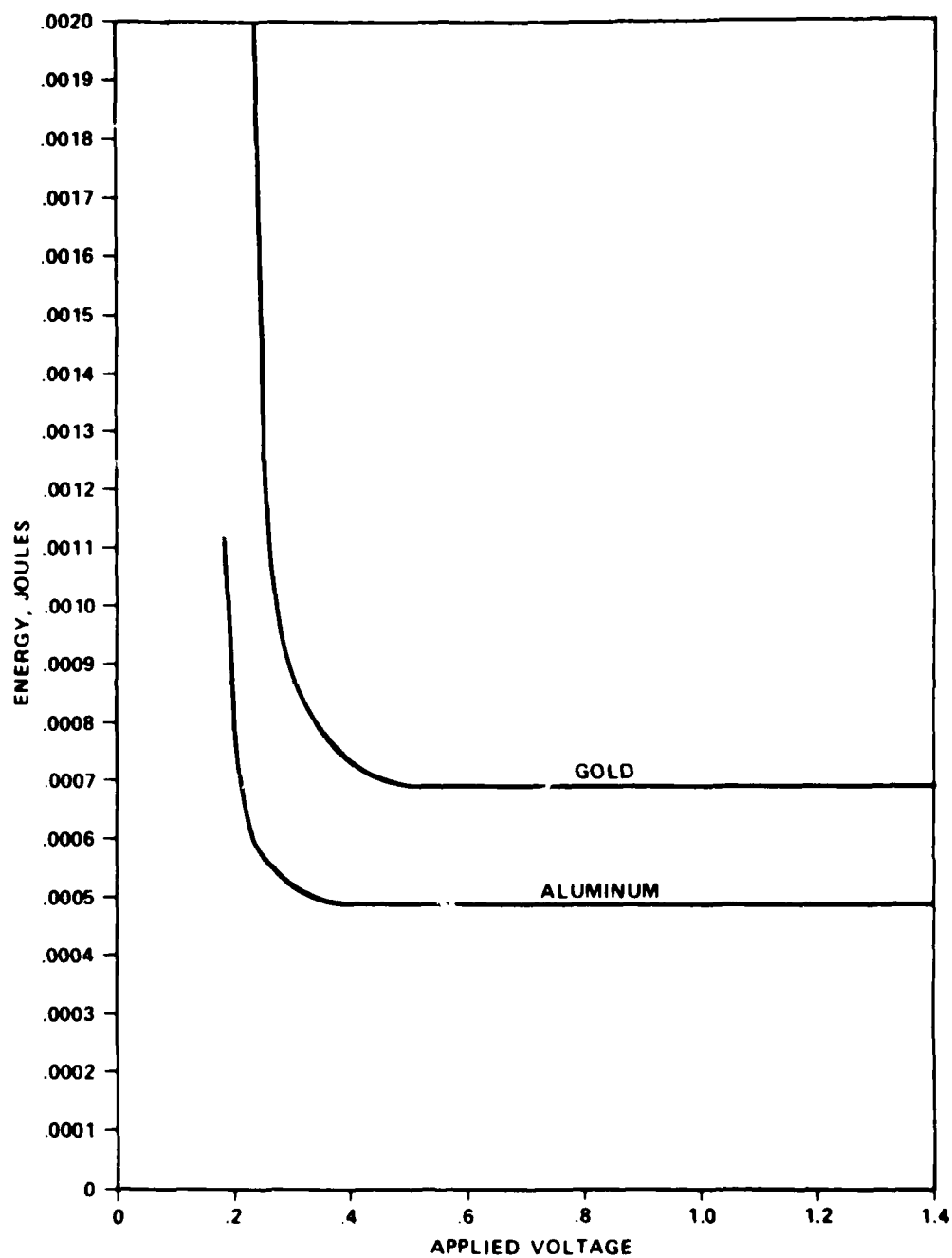   gold and aluminum wires .1 cm long

Figure 10.   Energy required to reach the melting point of .001-inch
diameter gold and aluminum wires .1 cm long

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REFERENCES

1. H.W. Baxter, Electric Fuses, Edward Arnold and Co., London, England (1950).

2. L.D. Yurk, "A New Approach to the Rating of Fuses for Electronic Circuits", IEEE Transactions, Vol IECI24, Nr 4, pp 317-321 (November 1977).

3. C.B. Wheeler, "The Performance of Electrical Fuses Under Impulsive Conditions, I: DC Supplies", Jour. Phys. D: Appl. Phys., Vol 5, pp 133-140 (1972).

4. H.S. Carslaw and J.C. Jaeger, Conduction of Heat in Solids, Oxford University Press, 2nd Edition, p 311 (1959).

5. M. Jakob, Heat Transfer, Vol 1, John Wiley and Sons, Inc., New York, pp 112-113 (1949).

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